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FLOODPLAIN AGGRADATION CAUSED BY THE HIGH MAGNITUDE FLOOD OF 2006 IN THE LOWER TISZA REGION, HUNGARY

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Abstract

The area of floodplains in the Carpathian Basin was dramatically reduced as a result of river regulation works in the 19th century. Therefore, the accumulation processes were limited to the narrower floodplains. The aims of the presented study are to determine the rate of accumulation caused by a single flood event on the active, narrow floodplain of the Lower Tisza and to evaluate the relations between the aggradation, flow velocity during the peak of the flood and the canopy. The uncultivated lands in the study area cause increased roughness which decreased the velocity of the flood, influencing the rate of aggradation. The highest flow velocity was measured on points where the flood entered to the floodplain and at the foot of the levee. These points were characterised by thick (over 50 mm) and coarse sandy sediment. In the inner parts of the floodplain flood conductivity zones were formed, where the vegetational roughness was small. In the inner parts of the floodplain the rate of aggradation was influenced by the geomorphology and the vegetation density of the area.

Key words: Lower Tisza, floodplain, accumulation, flow velocity, roughness

INTRODUCTION

The rate of floodplain aggradation is important from the point of view of increasing flood hazard and the dispersion of pollutants during flood events. Therefore, the rate of accumulation caused by single floods is studied along several temperate zone rivers (Gomez B. et al. 1997, Asselmann N. E. M. – Middelkoop H. 1998, Nagy B. 2002, Steiger J. – Gurnell A. M. 2002, Benedetti M. M. 2003, Oroszi V. et al. 2006). The accumulation is affected by several different factors which differ in time and space. The most widely cited and probably the most important factor is the geomorphology of the floodplain (Cazanacli D. – Smith N. D. 1998, Baborowski M. et al. 2007), the roughness of the inundated area (Rátky I. – Farkas P. 2003, Werner M. F. G. et al. 2005) and its land use (Knox J. C. 2006). Most studies analyse the pattern of the sediment deposited by a single flood event (Walling D. E. – He Q. 1998, Gábris Gy. et al. 2002) and its grain-size distribution (Hughes D. A. – Lewin J. 1982, Zhao Y. et al. 1999), or the connection between the flow velocity and the deposited sediment (Wyzga B. 1999).

The flood in 2006 was the highest recorded flood since 1842, when the gauge station network was established along the River Tisza (at the study area – Mindszent – the former record, 1000 cm in 2000 was replaced by 1062 cm on April 21 2006). In this area recent accumulation processes were studied after the 1998-1999, 2000 and 2001 floods (Kiss T. – Fejes A.

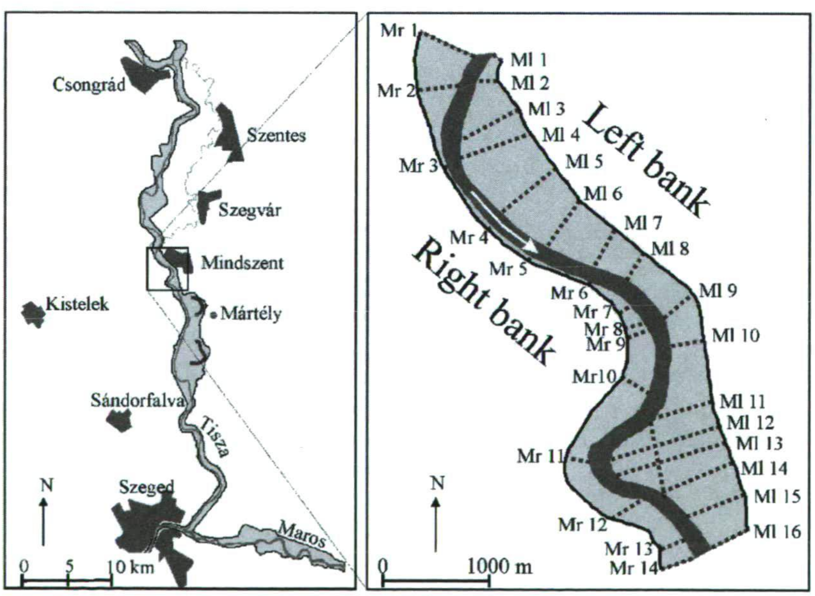

Fig. 1 The study area and the location of cross-sections, along them the depth of the fresh sediment, water velocity and the density of vegetation were measured

2000, Kiss T. et al. 2002). The aims of the present study are (1) to determine the accumulation rate caused by an extremely high flood and (2) to study the relationships between aggradation, flow velocity during peak flow and vegetation structure.

STUDY AREA AND THE 2006 FLOOD

The studied floodplain section is located in the Lower Tisza Region (*Fig. 1*), 6.5 km along the river (216.9-210.6 fkm), west of Mindszent. Here the River Tisza has three well-developed meanders; the lowermost is the sharpest. The artificial levees were built in 1890-1895, creating a narrow floodplain with quite irregular width, as the distance of the levee from the right bank varies between 35 and 560 m, while on the left side it is 110-1100 m respectively. The floodplain is flat, the difference in altitude slightly exceeds 2 m. The lowest features on the floodplain are swales and artificial sandpits and channels, and the higher ones are point bars and natural levees.

In the year 2006 two floods were recorded between April 10 and July 5 (*Fig. 2*). The first in April and May was 70-day-long, reaching a new record flood-level (1062 cm), and then a smaller and shorter flood-wave proceeded in June. The first was caused by the rapid snowmelt in the catchment and by the back-drainage of the Danube, while the second was due to high precipitation. Altogether the floodplain was covered by water for 102 days.

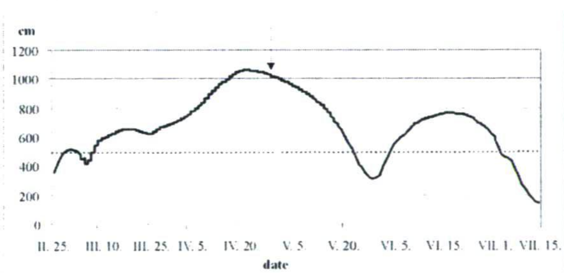

Fig. 2 Recorded water level at the Mindszent fluvio-meter in 2006 (data: www.vizadat.hu).
The arrow indicates flow velocity measure date

METHODS

Flow velocity measurements were carried out in order to determine the relation between flood flow and aggradation rate, and to reveal the role of vegetation in affecting flood flow. The number of flow velocity measurements were limited, as it had to be made within one day (April 30, 2006 at 1018 cm, just after the peak of the flood), because of the rapid falling. A calibrated Russian flow velocity meter (GR-21) was used from a motor boat, which was anchored. The measurements were made just on the left bank, along 12 cross-sections at 87 points. The exact location of each measurement-point was determined by Garmin GPS. Only at one point we measured the flow velocity at different depths to reveal the role of bushes in reducing flow. However, at each point we made only one measurement at the depth of 90 cm, partly because we wanted to make as many measurements as possible all over the floodplain, and partly because we could not hold it vertically in greater depth. The depth of the water column over the floodplain was 4.7 m in average (max. 5.2 m, min. 2.9 m).

At late summer the depth of the fresh sediment was measured along the same cross-sections as of the flow velocity measurements and along new cross-sections at both sides of the river (on ca. 500 points along 31 cross-sections). The leaf-layer of last autumn and the artificial surfaces created a reference level, therefore the depth of fresh sediment could be precisely measured. The grain-size distribution was determined by pipetten method and wet sieving.

Simultaneously with sediment measurements the arboreous vegetation of each point was described, namely species distribution and vegetation density. (Vegetation density was defined in different ways; their description can be seen below). In 3.0 x 3.0 m quadrates all the bushes and trees were counted and their periphery was measured at 1.0 m height. This mapping and the aerial photo, made in 2000, were used to create the canopy map of the area, using ArcView3.2. software. Based on the aerial photo the vegetation patches were identified, and based on the field measurements their average vegetation density was calculated.

Trees and bushes cover the largest proportion of the area (74.1%), and they play the most important role in increasing the roughness; therefore, these areas were classified from the point of view of flood conductivity. At first the quadrates were classified (*Table 1*) based on indices reflecting the number and size of trees. The *density index* was defined as the number of trees and bushes in the quadrate; the *periphery index* is the total sum of the periphery of the timber. In the final classification (*Table 2*) the above-mentioned two indices were summed (*canopy index*), but the density index was accentuated as according to our field observations it influences the flow velocity more.

In the quadrates belonging to the "sparse vegetation" class some old trees or in case of young planted forest no more than 10 trees grow, the underwood is sparse or missing. In the "dense vegetation" class at least 15 trees grow in a quadrate. These forests are undisturbed natural forests, planted poplar stands with sparse underwood. The "medium dense vegetation" category includes disturbed natural forests, poplar stands (at least 45 tree/bush per quadrate) and lands where *Amorpha* bushes appear. The "very dense vegetation" means all those areas (forests, former orchards and plough fields) which are overgrown by dense *Amorpha* bushes. Most of the study area (67%) belongs to the category of medium and very dense vegetation classes.

Table 1 Classes based on density and periphery indices

Density index	*Number of timber*
10	>45
9	41-45
8	36-40
7	31-35
6	26-30
5	21-25
4	16-20
3	11-15
2	6-10
1	1-5

Periphery index	*Sum of periphery (cm)*
5	>160
4	120-160
3	80-120
2	40-80
1	<40

Table 2 Vegetation classes based on the canopy index

Vegetation class	*Density index*	*Total periphery index*	*Canopy index*	*Number of quadrates*
Sparse	1-2	1-2	2-4	13
Dense	3-4	1-3	4-6	6
Medium dense	3-7	1-4	6-9	22
Very dense	6-10	1-54	10-15	21

Vegetation classes were then converted into roughness categories (*Table 3*) in order to determinate the mean vegetational roughness of the floodplain, following the roughness categories of Manning (Chow V. T. 1959). However, these categories might vary by the level of the flood: during smaller floods the trunk of trees and bushes submerged increasing the roughness, but as the water-depth increases, free flood flow might occur over the dense bushes (Chow V. T. 1959, Németh E. 1959). Besides, the roughness changes within the same forest, as it is smaller on roads but greater on the boundaries.

Table 3 Roughness categories (after Chow V. T. 1959)

Category	*Type of vegetation/land use*	*Mean roughness (n)*
1	River channel	*0.03*
2	Short grass, dirty road	*0.03*
3	Cultivated plough-field	*0.035*
4	Cultivated orchard, uncultivated plough-field, clearings	*0.05*
5	Inundated shallow depressions (sand-pit, scour channel etc.)	*0.05*
6	Uncultivated orchard	*0.07*
7	Forest with sparse underwood	*0.12*
8	Dense forest dense *Amorpha* bushes	*0.2*

RESULTS

Vegetation of the study area in 2006

The largest proportion of the study area (74.1%) is covered by arbours: most of the forests (67.4%) have natural underwood and only 5.7% has a cleared ground without underwood. However, the land use of the floodplain differs at the two banks of the river: the right side is almost totally covered by forest (willow, poplar and the invasive *Amorpha fruticosa)*; but the left side is close to the town, therefore, cultivated areas (orchards 10% and plough fields 10.8%) also appear. However, after the great flood in 2006 many of the orchards and plough fields remained uncultivated (4.7% and 8.8%, respectively). On fields, which remained fallow land for few years (4.9%) invasive species (*Amorpha fruticosa, Echinocystis lobata*) create almost impenetrable stands.

The roughness (n) of the study area is between 0.03 and 0.2, the mean roughness is 0.13, which is considerably high, falling into the category of "forest with sparse underwood". Over half of the territory (60%) is covered by the two highest roughness categories (*Fig. 3*), and less than 10 % is under 0.035.

Flow velocity changes at the floodplain

Due to the limited number of velocity measurements, no velocity distribution map of the floodplain was made. The cross-sections will be presented, which are grouped based on the velocity distribution along them. Some has the highest flow velocity in the middle of the cross-section, while others have higher flow velocities at their ends.

The first group contains such cross-sections (MI-2, MI-5, M I-8 and M I-13), where high flow velocity was measured at the middle of the cross-section. Their length varies between 200 and 1080 m (*Table 4*). The most characteristic is the M l-13 cross-section (*Fig. 4*), which is located in the inner bend of the lowermost meander. At the foot of the levee, covered by grass (n=0.03), high flow velocity (0.6 m/s) was measured, but in the planted poplar stand with dense underwood (n=0.2) the flow velocity reduced remarkably (0.15 m/s). In the inner part of the cross-section higher velocities were measured over a road (0.32 m/s) and on the boundary between the bushes and the plough field (0.46 m/s). Over the immerged dense bushes no movement was detectable under the depth of 90 cm (at the level and below the top of the bushes), therefore, we made more measurements at this point to find out the vertical velocity distribution (*Fig. 5*). Flow velocity was above 0 m/s only over the immerged bushes: the highest velocity was measured at the surface (at 10 cm 0.13 m/s), then it decreased to 0 m/s at the depth of 70 cm. This information suggests that in very dense *Amorpha* stands (n=0.2) the roughness is so high that it prevents the waterflow and thus, it is only possible over the bushes. At the bank (on the point-bar) 0.21 m/s flow velocity was measured. The mean flow velocity of the cross-section was 0.18 m/s. The phenomenon, that relatively high flow velocity is typical in the middle of the cross-section, is in connection with flood conductivity routes. In these cases longitudinal patches with low vegetation roughness (road or forest clearings) or deeper swales between two former point-bars enabled faster flow (*Table 5*).

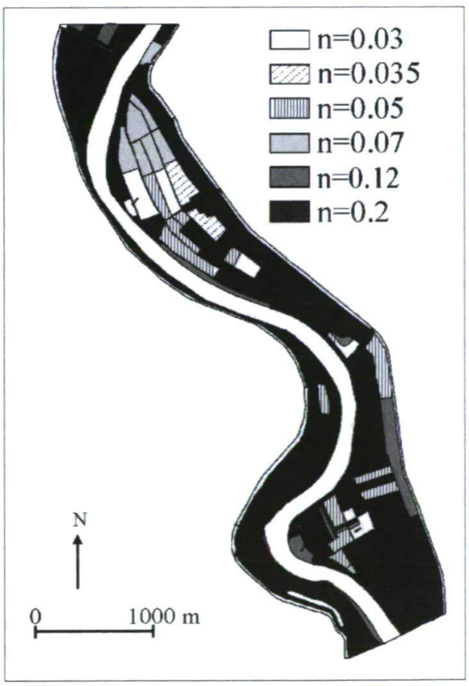

Fig. 3 Vegetation patches classified by their roughness (n)

Table 4 Data of cross-sections with high flow velocity in the middle

Cross-section	*Length (m)*	*Number of measurement points*	*Flow velocity (m/s)*			*Roughness (n)*
			min.	*mean*	*max.*	
M l-2	200	6	0	0.17	0.37	n=0.03-0.2
M l-5	650	11	0	0.15	0.62	n=0.03-0.2
M l-8	350	5	0	0.23	0.36	n=0.03-0.2
M l-13	1080	13	0	0.18	0.6	n=0.03-0.2

Table 5 Characteristics of the points situated in the middle of cross-sections and characterised by high flow velocity

Cross-section	*Description of the point*	*Distance from the river (m)*	*Flow velocity (m/s)*
M l-2	Road parallel to the river	55	0.37
M l-5	Low-lying surface, swale	305	0.37
M l-8	In clearings parallel to the river	103	0.36
M l-13	Road parallel to the river (2 points)	335 and 667	0.46 and 0.32

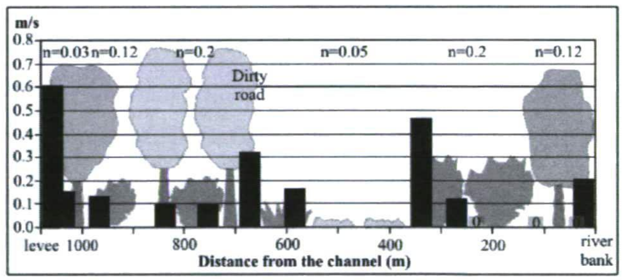

Fig. 4 Flow velocity distribution of the cross-section M l-13 (the vegetation type and the roughness are also indicated)

The second group of cross-sections is characterised by low flow velocity at their middle zones (M l-3, M l-6, M l-7, M l-9, M l-10 and M l-11). Their length varies between 330 and 630 cm (*Table 6*). The cross-section M l-6 is very typical for this group (*Fig 6*). Its length is 550 m, and the greatest flow velocity (0.56 m/s) was measured at the grass-covered levee (n=0.03). In the middle of the cross-section the roughness is higher (n=0.05-0.2), therefore, the flow velocity decreased to 0.12-0.2 m/s. Near the riverbank, in an old undisturbed gallery forest the flow velocity increased (0.53 m/s). The mean flow velocity of the cross-section is 0.22 m/s. In this cross-section group high flow velocity was typical at the river bank, partly because the morphological situation of the point (at inflexion and at convex bank, where the flood entered to the floodplain), and partly because the smaller roughness in forest with limited underwood or over the road running at the riverbank.

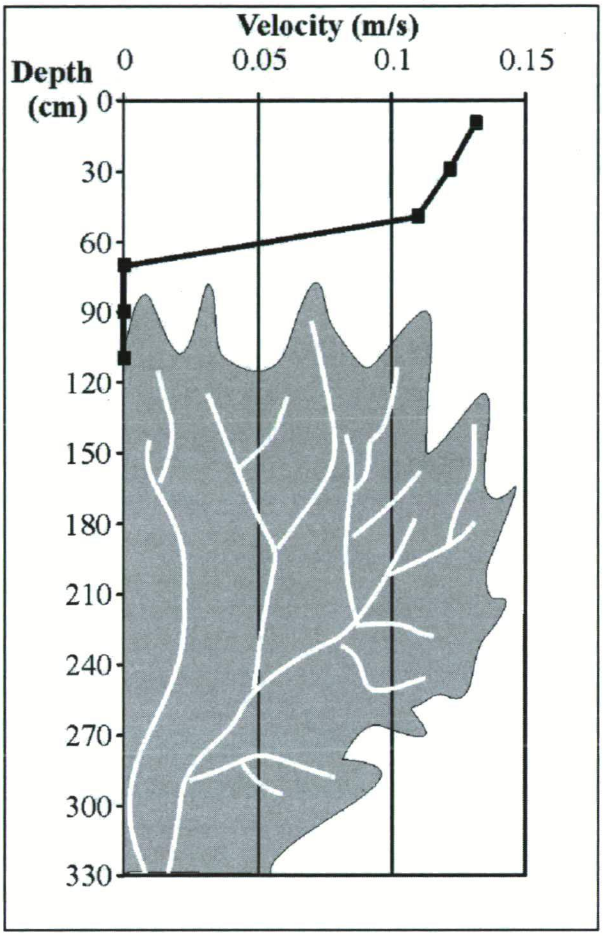

Fig. 5 Vertical velocity distribution over dense bush, at a point 225 m far from the channel

One longitudinal section (length: 680 m) was also made in the lowest and sharpest meander, between its inflexion points *(Fig. 7)*. At the upper inflexion point, where the flood entered to the floodplain (forest clearance), the greatest flow velocity (0.55 m/s) of the section was measured. As the distance increased from the bank, the flow velocity decreased. Along the section the roughness was almost the same (n=0.03) as it was used as ploughland. However, on the edge of the ploughland and a forest (n=0.12-0.2) smaller flow velocity was measured. At the end of the section, at the riverbank flow velocity was again higher (0.37 m/s), though not as great as at the upper inflexion point. The mean flow velocity of this longitudinal section is 0.34 m/s, much higher than any of the cross-sections, showing the existence of a flood conductivity zone.

Table 6 Data of cross-sections with low flow velocity in the middle

Cross-section	*Lenght(m)*	*Number of sampling points*	*Flow velocity (m/s)*			*Roughness (n)*
			min.	*mean*	*max.*	
M I-3	630	9	0	0.22	0.28	n=0.03-0.2
M I-6	550	7	0.12	0.22	0.56	n=0.03-0.2
M I-7	415	6	0.1	0.17	0.3	n=0.03-0.2
M I-9	360	5	0	0.15	0.27	n=0.03-0.2
M I-10	320	6	0.07	0.27	0.4	n=0.03-0.2
M I-11	560	8	0.5	0.3	0.68	n=0.03-0.2

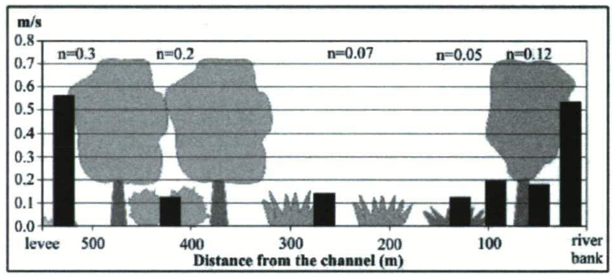

Fig. 6 Flow velocity distribution of the cross-section M I-6 (vegetation type and roughness are also indicated)

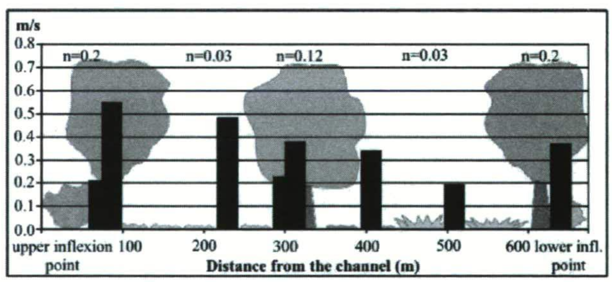

Fig. 7 Flow velocity distribution of the longitudinal section (vegetation type and roughness are also indicated)

Based on the results above, it can be stated that the greatest flow velocity on the floodplain is typical on patches running parallel to the river with low vegetational roughness, i.e. at the grassy levee, at roads and in poplar plantations with limited underwood. However, in areas invaded by *Amorpha* bushes the flow velocity drastically decreases, only over the bushes could the flood waterflow. Geomorphology of the riverbed determines where the flood can enter the floodplain, but in this case again the vegetation influences its efficiency. Morphology of the floodplain is also important as in the deeper swales, as well depending on vegetation conditions, greater flow velocity is typical.

Aggradation caused by the 2006 flood

The depth of deposited sediment was the greatest (50-500 mm) within 10-50 m from the channel. On the left side of the river, where the floodplain is narrow, the amount of aggraded sediment exponentially decreased with distance from the channel (*Fig. 8*), in accordance with earlier research (Walling D. E. – He Q. 1998). However, the left part of the floodplain is wider, therefore, the pattern of deposition was different, because other factors (geomorphology and vegetation) also influenced the aggradation. For example, we found patches with low aggradation rate. These areas were covered by very dense *Amorpha* bushes which acted as a barrier for the flowing water. Therefore, the water slowed down and even stopped among the bushes; thus, sedimentation took place on the boundary of the patch. The effect of floodplain geomorphology on aggradation was obvious where the floodplain was wide. In these cases thicker sediment was deposited in the deeper areas as in sand-pits, swallows and along a scour channel. At the points where the flood entered into the floodplain the aggradation was also greater.

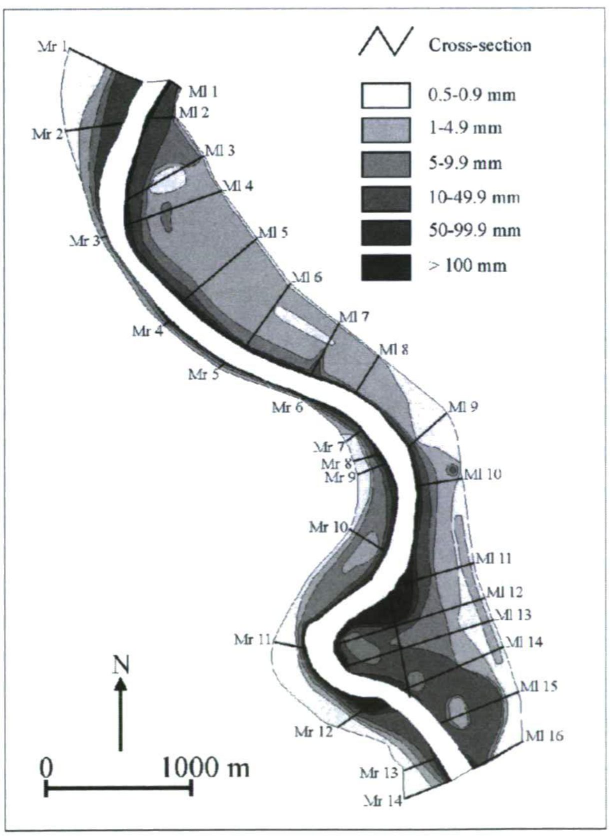

Fig. 8 Pattern of aggradation in the study area

The 31 cross-sections were grouped based on their length (*Table 7*). Group No. I contains those shorter than 150 m, while wider sections belong to the group No. II.

Table 7 Major characteristics of the studied cross-sections

Cross-section group			*Cross-section*	*Lenght (m)*	*Thickness of the fresh sediment (mm)*			*Mean flow velocity (m/s)*
					min.	*Mean*	*max.*	
No.I. Shorter than 150 m			M l-1	105	0.5	34.21	125	-
			Mr-3	45	0.5	1.45	6	-
			M r-4	60	0.5	22.43	135	-
			M r-5	60	0.5	10.76	70	-
			M r-6	35	0.5	49.91	130	-
			M r-7	143	0.5	30.81	230	-
No.II. Longer than 150 m	No.II/1. Exponential change of sedimentation		M l-4	710	0.5	9.3	260	-
			M l-11	555	0.5	45.93	150	0.3
			M r-1	560	0.5	7.14	48	-
			M r-2	400	0.5	2.98	15	-
			M r-9	220	0.5	13.59	500	-
			M r-10	300	0.5	5.99	186	-
			M r-11	230	0.5	19.25	500	-
			M r-12	353	0.5	65.15	250	-
	No.II/2. More peaks on sedimentation graph	II./2a	M l-3	625	0.5	8.11	200	0.22
			M l-5	675	0.5	5.45	120	0.15
			M l-8	310	0.5	8.77	144	0.15
			M l-9	370	0.5	13.82	280	0.15
			M l-10	330	0.5	18.04	170	0.27
			M l-12	1085	0.5	4.41	35	-
			M l-16	395	0.5	15.59	300	-
			M r-8	200	0.5	47.91	255	-
		II./2b	M l-6	550	0.5	6.16	140	0.22
			M l-14	750	0.5	7.75	80	0.09
			M r-13	250	0.5	4.71	90	-
			M r-14	347	0.5	34.44	280	-
		II./2c	M l-2	200	0.5	27.94	203	0.17
			M l-7	410	0.5	5.16	162	0.17
			M l-13	1080	0.5	12.61	150	0.18
			M l-15	585	0.5	8.33	20	-

The No. I. cross-section group includes the shortest ones (6). A typical example of this group is the Mr-4 cross-section which is only 58 m in length (*Fig. 9*). The greatest amount of sediment (135 mm) was deposited on the margin of the channel in a forest with very dense underwood. As far as 20 m from the channel the amount of accumulation was only 15 mm (decreased by 89%), and 50 m far it reduced to 3 mm. Here the aggradation from the channel towards the levee decreased exponentially (R^2=0.9182).

Group No. II. consists of cross-sections wider than 150 m (24). It was also divided based on the thickness changes of the sediment, namely whether it changed exponentially (No.II/1) or it had more peaks (No.II/2). Typical example for the first group is the Ml-11 cross-section starting from the upper inflexion point of the lowest meander (*Fig. 10*). Here the greatest amount (150 mm) of sediment was deposited within 180 m zone from the channel, in a poplar forest with dense *Amorpha* bushes. At 190 m from the channel the accumulation suddenly decreased (30 mm) at the border between a plough field and a dense scrub. Grain size distribution also changed, as on the banks the sediment consisted 95% sand, but at 190 m from the channel it was only 67%. Towards the levee thickness of the fresh deposit decreased and became finer.

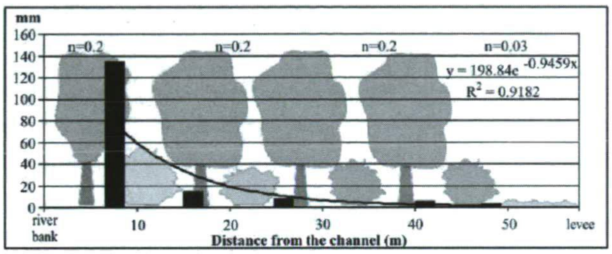

Fig. 9 Aggradation along the cross-section Mr-4

In some cross sections (No. II/2b) the maximum aggradation was measured at the channel and somewhere in the mid-zone of the cross-section. An example is the Mr-7 cross-section where 230 mm sediment was deposited on the bank (*Fig. 12*), but in 10 m it decreased to 180 mm, and in 25 m far it decreased further to 22 mm. From this point, increasing amount of sediment was measured (max. 60 mm) towards the levee.

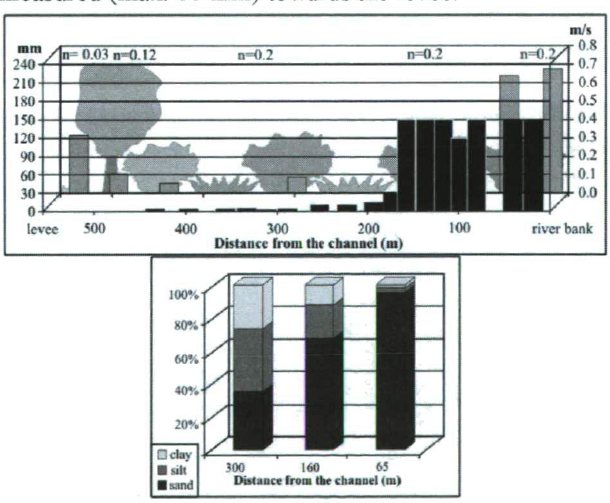

Fig. 10 Aggradation along the cross-section Ml-11 and the grain size distribution of sediment

In case of some cross-sections (i.e. No. II/2) more peaks appeared on the aggradation graphs. In some of them (No. II/2a) the greatest accumulation was measured at the bank and near the levee. One of them is the Ml-3 cross-section, where at the bank 200 mm thick sediment was deposited, but already at 40 m from the bank the sedimentation decreased to 38 mm, and at 150 m only to 6 mm, respectively (*Fig. 11*). In the middle part of the cross-section only very thin (less than 1 mm) sediment was deposited on a plough field. Near the levee (490 m far from the river) again thicker, 3-10 mm sediment accumulated in the deeper lying sand-pits.

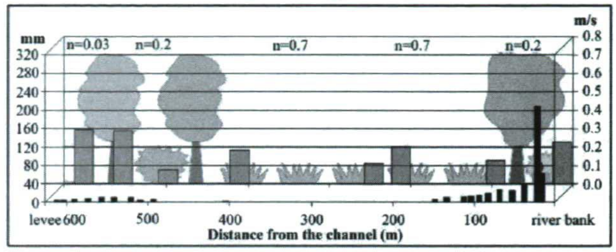

Fig. 11 Aggradation along the cross-section Ml-3

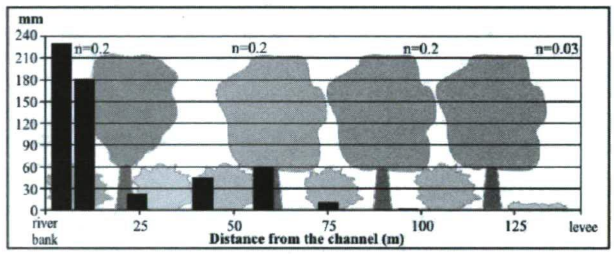

Fig. 12 Aggradation along the cross-section Mr-7

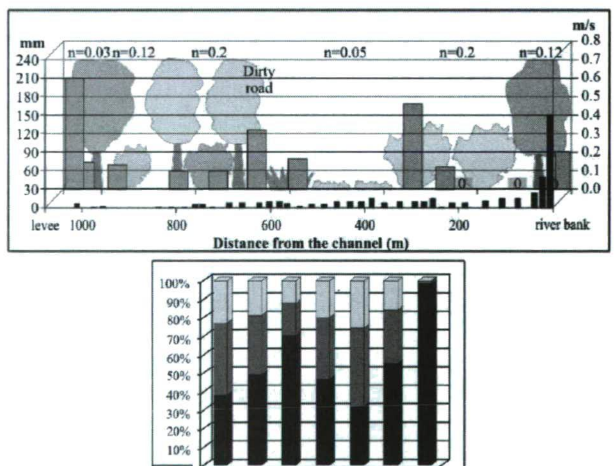

Fig. 13 Aggradation along the cross-section Ml -13 and the grain size distribution of sediment

Altogether four such cross-sections exist (No. II/2c) where three aggradation peaks were detected. For example, in the Ml-13 cross-section the accumulation rate decreased exponentially (from 150 mm to 8 mm) in 200 m from the bank (*Fig. 13*), and the sediment became finer. In the middle of the section (ca. 580-680 m from the channel) the amount of sediment increased (9-15 mm) and became coarser. The third sediment peak (3-7 mm) was measured in the sand-pit, near the levee, 950-1010 m far from the river. It suggests the existence of a flood conductivity zone; this fact, nevertheless, is also supported by the geomorphology (swale).

Based on the results listed above, it could be stated that the primary factor influencing the aggradation on the floodplain is the distance from the channel (*Fig. 14*). The greatest depth of sediment is deposited in form of point-bars and levees. From the banks the accumulation exponentially decreases towards the levees. The next factor is the pattern of the channel, as (1) where the water enters to the floodplain the aggradation is much higher compared to the neighbourhood, and (2) in case of the sharper bend the floodplain plays important role in flood conductivity, and therefore, in the flood conductivity zone more sediment was deposited.

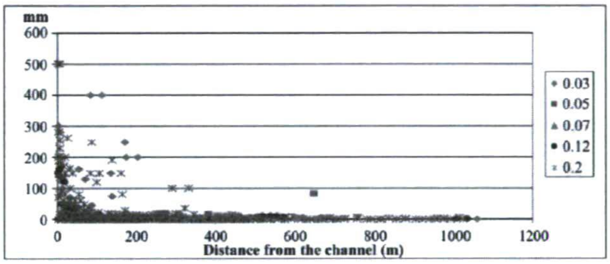

Fig. 14 Distance from the channel is plotted against the rate of accumulation in case of different roughness

Geomorphology belongs to the local factors influencing the rate of aggradation, as in deeper areas (e.g. swale, scour-channel and sand-pit) the accumulation is always greater. Far from the channel vegetation plays the most important role in the process of sedimentation. Here the very thick bushes prohibit the waterflow, thus the aggradation is smaller (less than 1 mm) than in areas at similar location (similar distance from the channel and similar geomorphological situation). Due to the above-mentioned local factors the exponential function can be applied only where the floodplain is narrow (max. 150 m).

The grain-size distribution of the sediment changes, as the sediment becomes finer departing from the channel. However, in flood conductivity zones coarser material was found in accordance with the flow velocity. The coarsest material is deposited in the area of natural levees and point bars.

CONCLUSION

The present land use of the area causes increased vegetational roughness (mean n=0.13), as 74% of the study area is covered by forest with dense underwood, uncultivated orchards and ploughlands. Increased roughness highly influences the waterflow: the denser the vegetation is the slower the waterflow on the floodplain becomes. The highest flow velocity is typical at those points where the flood enters the floodplain and at the foot of the levee. On the floodplain, where the roughness is small and therefore flow velocity is high, flood conductivity zones are formed running parallel with the river.

The rate of aggradation is primarily determined by the distance from the channel. The thickest (over 50 mm) and coarsest (95% of sand) sediment is deposited within 10-50 m from the channel, in the zone of point-bars and natural levees, independent of vegetation. The sediment became finer and the rate of aggradation decreased with the distance from the channel. In the flood conductivity zones, which run parallel with the channel and where the vegetation is sparse, thicker and coarser sediment was deposited.

In the narrow floodplain sections the rate of aggradation fits the exponential curve (R^2=0.8-0.9) as it was described in previous studies. However, where the floodplain is wider than 150 m, the aggradation is influenced by not only the distance from the channel, but also by the geomorphology of the area and the density of vegetation.

The pattern of fresh sediment follows the channel; however, in the southern sharp bend the flood makes a "short-cut", as it was ıeflected not only by higher flow velocity but also by greater aggradation. Patches characterised by small aggradation develops under very dense vegetation, where the flow velocity decreased to zero. It means that the very dense vegetation acts as a barrier against waterflow, therefore, sedimentary processes are more pronounced on their edges and much less sediment is deposited within.

Comparing these results with earlier measurements made in the same study site along the same cross-sections (Kiss T. – Fejes A. 2000, Kiss T. et al. 2002), we can state that the pattern of aggradation was very similar in each year. The rate of aggradation slightly differed, as in 2000 the mean accumulation on the floodplain was 20.5 mm (Kıss T. et al. 2002) and now it was 18.9 mm.

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